Future Trends in Construction and Maintenance Management of Drainage Systems in Traffic Tunnels

FUTURE TRENDS IN CONSTRUCTION AND MAINTENACE MANAGEMENT OF DRAINAGE SYSTEMS IN TRAFFIC TUNNELS

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ABSTRACT

Scaling in tunnel drainages causes high cleaning and repair expenses, constrains traffic and can endanger tunnel and roadway stability. Based on deductively explained scaling processes, and taking the special demands of the new preventive maintenance method "hardness stabilization" into account, design requirements for drainages have been developed with the aim of achieving "low scaling", "durability" and "maintenance support". Observing these guidelines can lead to a reduction of more than 46 per cent in maintenance expenses, drainage durability can be significantly increased and repair expenses sustainably reduced. The presented methods and guidelines therefore have a great life-cycle effect for tunnels and can, furthermore, be transferred to other structures.

1 INTRODUCTION

Free-drained tunnels are an economical alternative to pressure-tight and pressure-controlled drained tunnels. The inner shell has only to ensure permanent rock support(1,2,3,4). But significantly higher maintenance costs accrue for newer free-drained tunnels than for tunnels built in the 19^{th} and early 20^{th} centuries. The higher maintenance expenses are caused by scaling in the drainage pipes, which must be removed regularly since drainage operability will otherwise be restricted. As a result, water can escape out of the manholes and seep into the roadbed, leading to impaired stability as a result of the combination of moisture and dynamic strains. Therefore traffic safety is endangered and expensive repair measures will become necessary. Furthermore water pressure can build up on the tunnel shell due to constriction of ground drainage; this endangers the stability of the tunnel shell.

1.1 State of the art

Old tunnels were drained with open drainage ditches along the side walls. In newer tunnels appropriate drainage systems (Figure 1) have to be incorporated to meet the tunnel climate requirements of operators. All tunnel-drainage systems have specific scaling appearances even if water is drained in different ways in the different systems. Apart from variable scaling appearances in the pipes, heightened scaling can very often be found in the manholes. Moreover, clear interdependencies between increased scaling and special tunnel structures (e.g. ventilation shafts, portals, cross cuts, profile enlargements, rescue galleries) can be observed. These observations indicate that the choice of construction materials influence scaling.

The precise causes for scaling were previously unknown, which is why inadequate solutions only could be suggested. Due to the unknown individuality of the influences, the scaling problem was even exacerbated by potential solution measures in single cases. Depending on the individual combinations of different influences a solution measure can have both a positive and negative effect. As far as is known today, there is no generally valid solution for reducing scaling in tunnel drainages, which is why individual solutions have to be developed for every single tunnel. This is also why tunnel operators weren't able to do more than regularly remove the accruing scale in the past.

Table 1: Post-sediment pipe-cleaning methods of sewage technology applied for tunnel drainage cleaning, their efficiency and their impact on durability

Cleaning Method	Efficiency	Impact on durability
High-pressure water flushing with fixed nozzles, with 150 l/min at 120 bar at nozzle	Appropriate for silty, soft and medium-hard deposits with low to high quantity	Low risks for damage pipes
Highest-pressure water flushing with rotating nozzles, with 700 bar (in extreme 1000 bar) at high-pressure pump	Appropriate for hard deposits with low quantity on bottom of the pipes	High risk for cutting the wall of the pipes in case of stagnant nozzle
Rope and chain flails; Rope and chain scrapers	Appropriate for hard deposits with medium quantity around the complete pipe profile; not for complete filled pipes	Medium risk for damage the pipes at correct use; high risk for damage non-round pipes as well as in case of uncorrect usage
Impact drilling cutters	Appropriate for medium and hard deposits with high quantity (complete filled pipe profile)	High risk for milling and cutting off greater pieces of pipe wall

The sewage technology methods used for cleaning the drainage systems are only moderately qualified for dealing with the often hard, partially very hard scale in tunnel drainages. Table 1 shows post-sediment pipe cleaning methods presently used, their fitness for different scaling forms and their impact on the durability of tunnel drainages.

In recent years the scaling problem has received more and more attention. The operators were looking for solutions to remove the accruing scaling as efficiently and economically as possible, and prompted research to both explain scaling causes and develop solutions to prevent/reduce high maintenance and repair expenses. The following results were developed at the Swiss Federal Institute of Technology Zurich (ETH Zurich) on behalf of the German Railways.

1.2 State of research

Currently there are only a few research works focusing on the causes of scaling in tunnel drainages. In Switzerland Wegmüller(5) was one of the first to address with this problem. But most of the waters analyzed are ascending deep-ground waters, which is why his results can be transferred only partially to tunnels influenced by descending seepage/ground water. Ascending ground water not only generally has a significantly higher temperature but also a

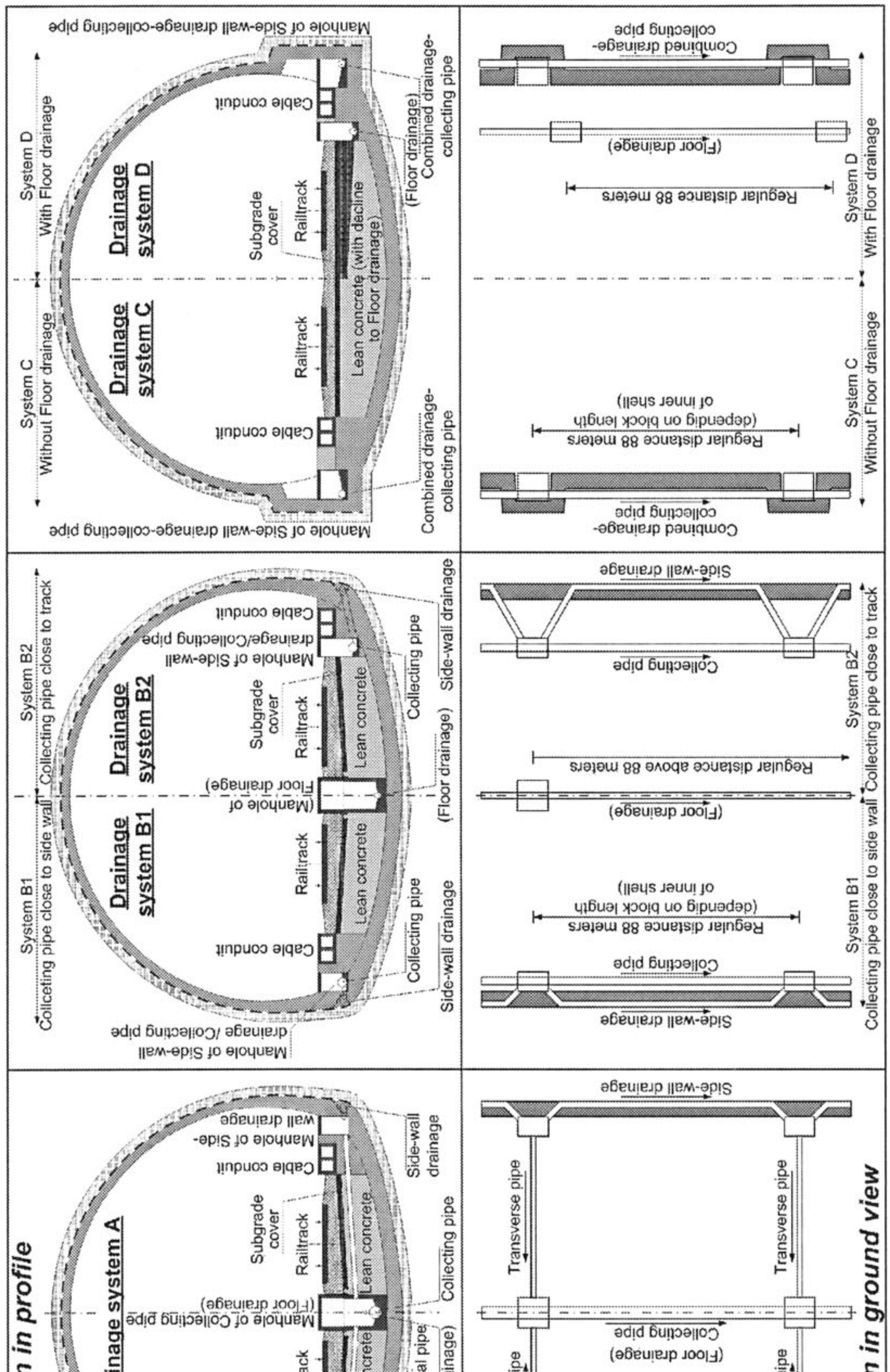

Figure 1: Different types of drainage systems in European traffic tunnels

much higher degree of mineralization than descending water. The scaling mechanisms in tunnels are considerably more similar to those of ground-water wells(6,7,8) or flat-roof drainages(9,10).

More research activities can be detected in the field of designing and building tunnel drainages to cope with the problem of scaling; most of them use the inductive method. In 11, 12, 13 und 14 recommendations for building new tunnel-drainage systems were derived from observations in existing tunnels. At the Saukopf tunnel (Germany) negatively interacting drainage waters were separated retroactively(15). In addition to these inductive optimizing approaches, some experimental research works exist, which are simulating scaling in parts of tunnel drainages and analyzing the behavior of selected construction parts and materials(16,17). But explaining the causes of scaling isn't the focus of these studies. First analyses that deal with the scaling problem caused by new building materials and construction methods are 18,19 and 20.

1.3 Research gap and objectives

Recapitulating experience to date, the design of a drainage system is a substantial factor for scaling, in addition to the influence of materials. Depending on the individual scaling quantity, expensive maintenance becomes necessary, which strains the drainages. Depending on their resistance damages develop, which cause high repair expenses to maintain operability and further maintenance ability.

Apart from these fundamental design requirements for tunnel drainages, resulting from scale formation and cleaning, new maintenance methods also demand adjustments. Therefore a tunnel drainage has to meet the following three main criteria:
- Low scaling;
- Durability; and
- Support of maintenance methods.

1.4 Research methodology

In line with the general research framework for production science at the Institute for Construction Engineering and Management of ETH Zurich(22), the chosen research approach comprises a model level between reality and theory, on which the complex reality can be reproduced abstractly(23) and theorized(24,25). Depending on starting point and objectives of the research both induction(26) and deduction methods(27) were used to gather knowledge. Induction means the general theorization of particular observations and is suitable for structuring the complex diversity of reality(28). Derivation of explanations was conducted deductively, based on theory. The role of scientific natural research was to construe phenomenological parameters on an unobservable level – the theory(29).

2 MAIN MECHANISMS FOR FORMATION OF SCALING

In order to investigate the causes of scaling in tunnel drainages the composition of emerging scale first had to been analyzed to narrow down the scope of influences. Afterwards the practical experience was interpreted using general theories. The scaling samples of tunnels influenced by descending seepage/ground water were composed nearly completely of calcium carbonate. Therefore it was possible to restrict the investigation of scaling causes to processes of lime solubility. Model calculations were executed after formulating fundamental effect mechanisms, which were verified again with practical experience(30). The scale formation in tunnels drainages caused by descending water depends primarily on the following influences.

a) Building materials used for tunneling have a substantial influence on the mineralization of drainage water. When injection/anchor grouts, shotcrete and filter concrete etc. seep, the water hardness and pH-value increases. For these reasons no conclusions about later scaling in drainages can be drawn from analyzing uninfluenced ground water as a rule.

b) pH-value of drainage water is very often heightened as a result of material elution. Due to high pH-values the lime solubility of water is significantly decreased. Heavy scaling can be expected and observed particularly at the points where water with a high pH-value (e.g. out of ventilation shafts, portals, rescue galleries) mixes with limy water with a low pH-value.

c) Temperature influences the solubility of gases in water. Given the direct proportionality between lime solubility and carbon-dioxide concentration, and the decrease in carbon-dioxide solubility as temperature rises, scaling can be expected at points where drainage water is warmed.

d) Aeration of drainage water changes the concentration of dissolved carbon dioxide. Water containing a high carbon-dioxide concentration and therefore much lime loses carbon dioxide by aeration, which is above the atmospheric equilibrium. As a result, less lime can held in solution, and scaling occurs. Furthermore, water, which contains high concentrations of calcium hydroxide due to extensive contact with cementous materials, is enriched with carbon dioxide by aeration, whereby scaling occurs. At points like water falls where aeration occurs, high scaling is expected and can be observed.

e) Evaporation of water reduces solvent whereby the concentrations of dissolved salts increase. Scaling occurs where solubility is exceeded.

3 NEW MAINTENANCE METHODS

At present, scale formation in tunnel drainages can only be influenced by the inhibitor polyaspartic acid (PAsp) because of specific system features and environmental demands. PAsp inhibits, elongates or retards scale formation. It is produced synthetically but also related to natural aspartic acid, whose inhibiting effect is used primarily by crustaceans and corrals.

The effect of polyaspartic acid on scale formation was first reproduced using theoretical considerations, based on generally accepted chemistry theory. Hypotheses about expected observations of targeted laboratory tests were formulated on the basis of these considerations. The occurrence of the expected results allows both the theoretical considerations to be extended to reality and the execution of tests in tunnels. Based on these practical tests in three tunnels of the German Railways, prognoses about the cost-efficiency of hardness stabilization were developed (Figure 2).

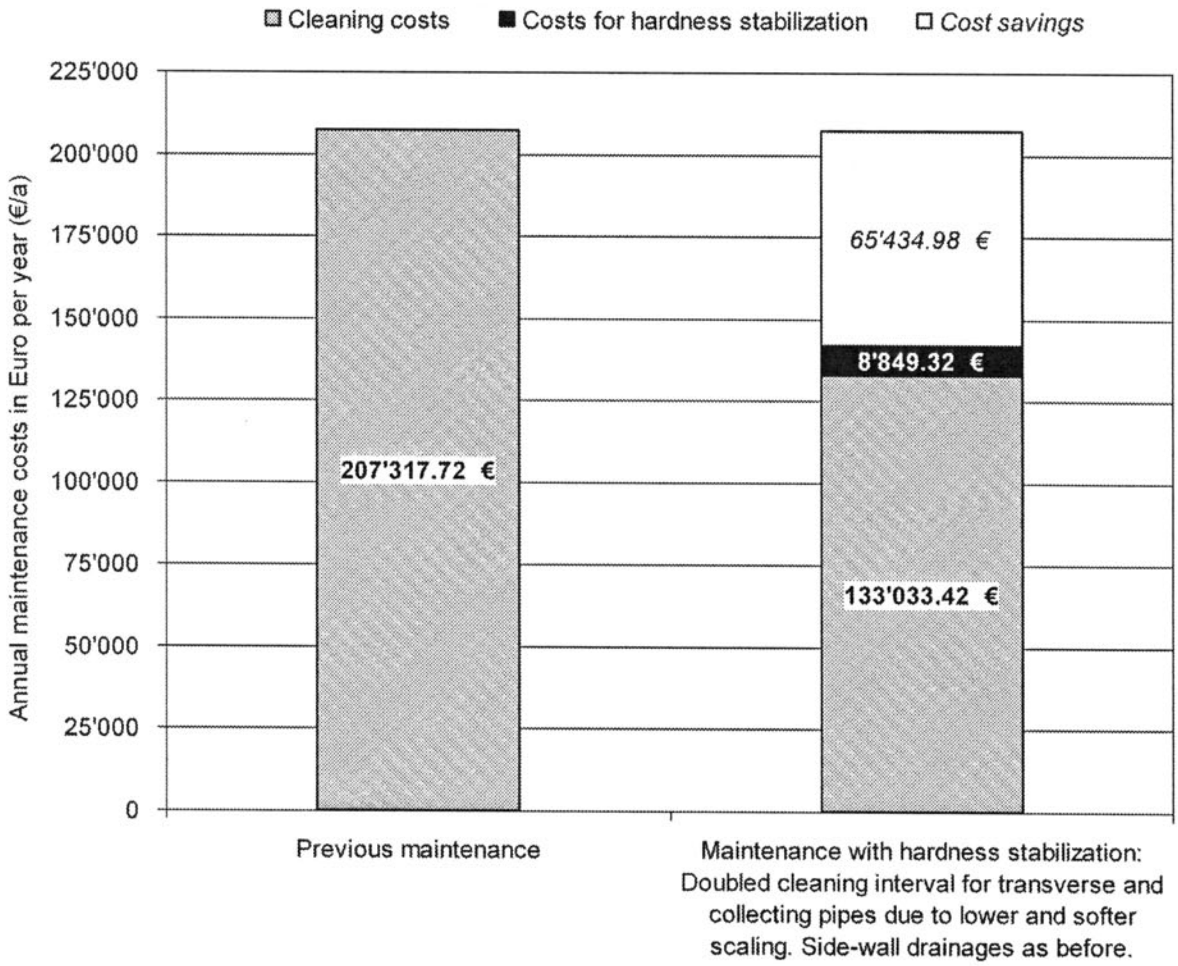

Figure 2: Previous annual maintenance costs of a 3 kilometer tunnel in comparison with annual maintenance costs using hardness stabilization

4 REQUIREMENTS ON DESIGN OF TUNNEL DRAINAGES

Based on the inductively derived scaling causes, design requirements for new tunnel drainages could be concluded deductively to achieve the objectives „low scaling", „durability" and „support of hardness stabilization/post-sediment cleaning". Every single drainage part was analyzed and theoretically optimized. Subsequently the interactions between the parts were scrutinized. The interactions were balanced and a basic reversibly adjustable drainage system was created.

Table 2: Requirements on single tunnel drainage parts regarding the different objectives "Low scaling", "Durability" and "Support of maintenance"

Requirements on tunnel-drainage parts regarding				
Part	Low scaling	Durability	Support of hardness stabilization	Support of post-sedimentum cleaning
Drainage packing	1.21 not cement bounded	2.21 no loose fill	Hardness stabilization of drainage packings also used, but optimisation needs further reseach	No cleaning possible
	1.22 no limy aggregates			
	1.23 no fine materials/ fractions	2.23 washed round gravel		
	1.24 no tailback with drainage water			
Drainage pipes	1.31 scaling-neutral material	2.31 single layer pipe wall	3.31 continuous water flow	4.31 no pipe bends
	1.32 reduced aeration of water	2.32 heightened wall thickness		4.32 wide infiltration slots
	1.33 circular pipe profile	2.33 circular pipe profile		4.33 circular pipe profile
	1.34 small pipe diametre (Q/A_o)		3.34 inflow/outflow much as possible	4.34 high pipe diametre
	1.35 no turbulences/ no waterfalls			4.35 small manhole-distance
	1.36 plane inner pipe wall			
	1.37 moulded pipe couplings			
	1.38 separation of interacting water			
Manholes	1.41 gutter: scaling neutral material	2.41 robust material	3.41 providing continuous flow	4.41 accessibility for pipe cleaning
	1.42 continue circular pipe profile	2.42 no sharp arris	3.42 stearing inflows and outflows	
	1.43 smooth, plane gutter wall		3.43 place for hard-ness stabilizer	
	1.44 no turbulences/ no waterfalls			
	1.45 gutter moulded to pipe geometry			
	1.46 airtight cover (piston effect)			
	1.47 separation of interacting water			

At first the water seeps through the temporary support, in many cases made of shotcrete. After that the water reaches the drainage packing, which covers the drainage pipes in the side walls. To prevent further changes in water mineralization the drainage packing should be made of filter concrete, which is not cement-bounded and contains no limy aggregates as well as fine materials and fractions respectively (Table 2, No. 1.21/1.22/1.23). But to prevent gravel falling into the pipes in case of damage, the drainage packing shouldn't be made of loose fill. The washed round gravel should be bound using scaling-neutral resin (Table 2, No. 2.21/2.23). To prevent further changes in water mineralization the drainage water shouldn't accumulate in the drainage packing (further contact with shotcrete) but be strictly drained off (Table 2, No. 1.24).

The prevention of changes in water mineralization has to continue consequently in the pipes and manholes because every change can cause scaling. Therefore the pipes and gutters in the manholes should be made of scaling-neutral material (Table 2, No. 1.31/1.41). Only pipes with a single layer pipe wall with heightened thickness should be used to provide high resistance against cleaning strain (Table 2, No. 2.31/2.32). Furthermore, the pipes should be laid linearly without bends (No. 4.31). Accessibility for cleaning and repair equipment through the manholes has to be possible (No. 4.41). Wide infiltration slots in drainage pipes can be reopened much more easily than small slots (No. 4.32). Only circular pipes should be installed in tunnels in future (Table 2, No. 1.33/2.33/4.33). The gutters in the manholes must continue the circular profile (No. 1.42).

A large pipe diameter permits the use of effective post-sediment cleaning methods (Table 2, No. 4.34), but leads to a low water flow/surface-ratio, where high evaporation and gas exchange can occur. That's why the pipe diameter must be limited in the interest of low scaling (No. 1.34). The diameter depends on the water infiltration and should be about 200 millimeters minimum to allow for cleaning.

In recent years the manhole distance was reduced in many European tunnels to allow for increased cleaning (Table 2, No. 4.35). But this leads to higher construction costs and to higher aeration of the drainage water. Manholes generally influence water flow. Furthermore a piston effect from traffic leads to turbulences and aeration of drainage water. Therefore it is recommended that the cover of the pipe conductions in the manholes be sealed hermetically (Table 2, No. 1.46) and a manhole distance of about 90 meters be executed.

To further reduce water aeration (Table 2, No. 1.32) no waterfalls should be installed in the whole drainage system, as was the case to date, and turbulences should be avoided (No. 1.35/1.44). The gutters in the manholes must be molded to pipe geometry (No. 1.45), made of robust material and should have no sharp edges because of the risk of damages from cleaning (No. 2.41/2.42). Every pipe coupling should be molded accurately (No. 1.37). The inner pipe wall and the gutter surface should be even and smooth (No. 1.36/1.43). A laminar flow must be provided by an adequate slope.

A typical drainage section in European tunnels is 88 meters long. But very often only a low water quantity infiltrates over such a section. Therefore a drainage system conducting the water from one section to the next (cp. Figure 1, systems C and D) is best for reducing evaporation and gas exchange with the atmosphere by providing a high pipe filling level. This water conduction is also necessary for the efficient use of hardness stabilization because the water inflow at the beginning transports the hardness stabilizer into the pipe (Table 2, No. 3.31). The more stabilized water that flows into a section the more infiltrated water can be stabilized, leading to less scaling (No. 3.34).

But differently mineralized water can influence other water when mixed together, whereby massive scaling can occur (cp. Paragraph 2 b). Depending on topography, geology, hydrogeology, changes in tunneling or sealing/drainage methods and special tunnel parts, differently mineralized drainage waters appear in many longer tunnels, which leads to scaling at the mixing points. For these tunnels a basic reversibly adjustable drainage system was developed (Figure 3).

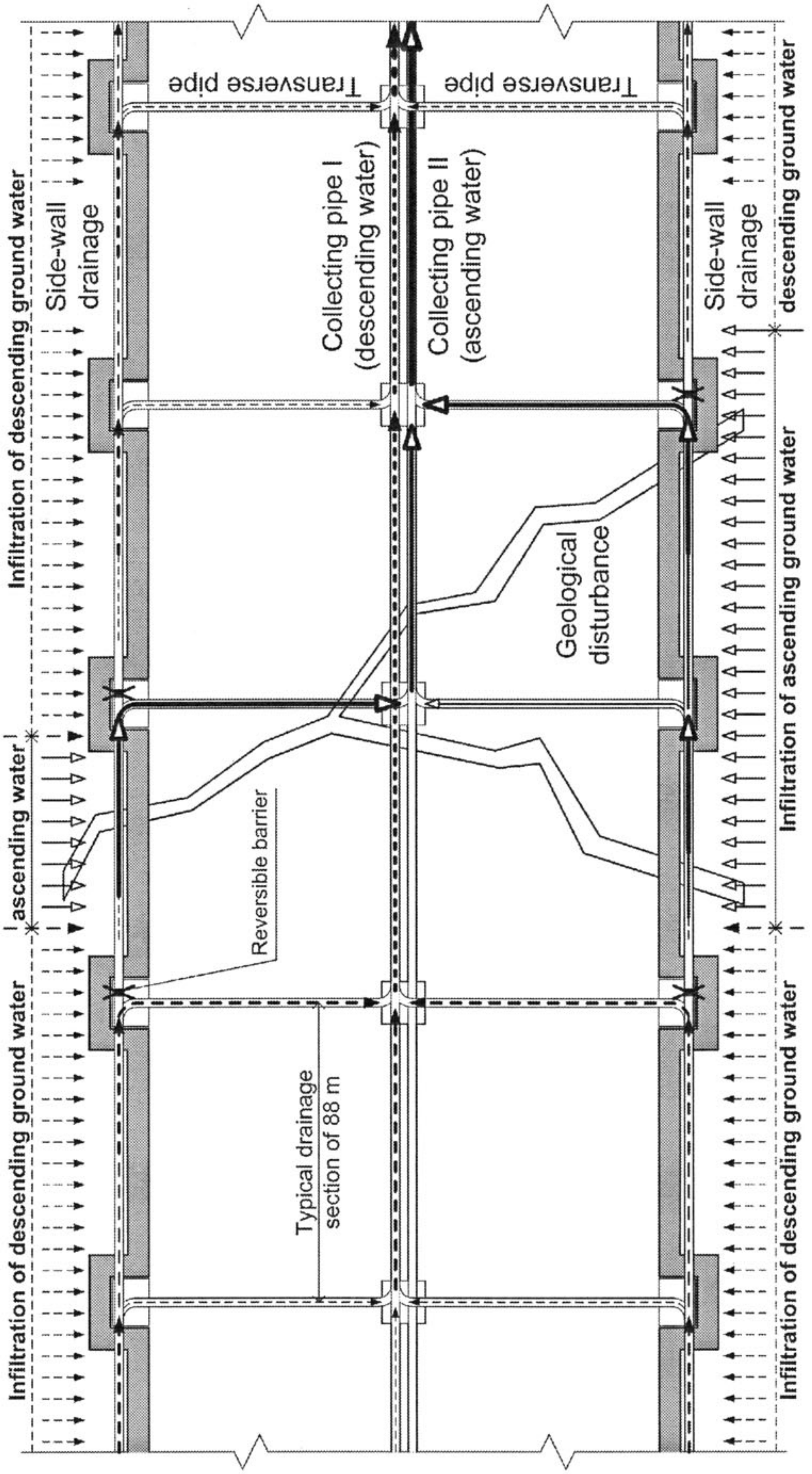

Figure 3: Basic reversibly adjustable drainage system which provides future adaptations on changing individual scaling factors; separation of descending and ascending ground water as example

The main benefit of this basic drainage system is a conduction of compatible drainage water through the side-wall drainages (cp. Table 2, No. 3.41). Optimal pipe filling is guaranteed by overflow funnels in each manhole (cp. Table 2, No. 3.42).

If an infiltration of incompatible water (ascending water in the example (Figure 3)) can be observed as a result of extreme scaling the mixing of the incompatible waters can be stopped by reversible barriers in the inflow of the affected section. Thus the whole collected water flows through the transverse pipe into the suitable collecting pipe. The incompatible water will be collected and drained separately. To prevent scaling by mixing the two incompatible waters, the second water will be led through transverse pipes in the second collecting pipe. Therefore two incompatible waters can be collected and led off the tunnel separately without interactions. Furthermore, separate stabilizing measures for the individual waters can be performed (cp. Table 2, No. 3.43).

5 CONCLUSIONS

The presented research work attempted to be one of the first to theoretically both deduce measures against scaling and reduce maintenance and repair expenses of tunnel drainages. The mechanisms of scale formation were inductively developed based on scale analyses involving generally accepted chemical laws. The reliability for the developed explanations was obtained by further targeted observations in practice because no logical rules exist for inductive conclusions and several equivalently competing causal explanations can be established(27).

The positive effects of hardness stabilization using polyaspartic acid were confirmed in numerous laboratory tests(31 to 38). Qualitative tests in different tunnels of the German Railways have shown positive manipulation of scale formation(39). The practical experiment of Maidl (40 pp. 357-358), carried out autonomously in the Saukopf tunnel, confirms the positive effect.

The conception of the basic reversibly adjustable drainage system was hypothetically deductive(29, p. 41). For purposes of verification, the results of inductive research from other institutions were included(11,12,13,16). The deductive, theoretically conducted research methodology has proven to be very effective for quickly developing targeted problem-oriented solutions. The presented results can be directly transferred to practice and enhance the cost-value ratio of tunnels and other structures with a drainage system, like dams, civil-engineering structures, flat roofs etc. The failure probability of the drainages is reduced by decreasing scaling risk, on the one hand, whereby the stability of both the tunnel and the transportation route is increased. On the other hand, the maintenance expense is directly reduced and the utilization capacity is directly enhanced whilst repair expense is indirectly reduced and the life cycle is indirectly increased.

Further research needs to focus on investigating the operation mode and verification of effectiveness of hardness stabilizers in tunnel drainages in view of persisting unclarity(40, pp. 347-353). In the past the drainage pipes installed in tunnels were tailored to the drainage of soil and not to the conditions prevailing in tunnels (e.g. to narrow infiltration slots, flat flow bed instead of a channel). In the recent past new pipes for tunnel drainages have actually been developed, but these are still based on the originally used pipes. In future therefore further developments are required, for instance in materials, to obtain pipes that fulfill requirements even better and ensure long-term durability.

Cleaning methods from sewage technology (Table 1) are presently being used in tunnel drainages, often with high/extreme cleaning force to enable infiltration slots at the pipe crown to be reached with sufficient power, since the cleaning force of these methods concentrates mainly on the base of the pipe. Therefore the bases of the pipes are often exposed to extreme stress, which leads to damages and avoidable repair expenses. This is why cleaning methods need to be developed specifically to meet tunnel requirements.

Further research is necessary in the field of structural scale avoidance. Here issues primarily surrounding materials and construction have to be resolved to reduce the influence of construction materials on the water. In order to achieve these objectives, fundamental research into a precise explanation of the hydraulic regime of ground water around a tunnel is also needed.

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